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AUTHOR(S):

Banno, Hayaki; Saiki, Jun

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THE CALCULATION OF MEAN CIRCLE SIZE UNDER CROWDING

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Calculation of the mean circle size does not circumvent the bottleneck of crowding

Hayaki Banno and Jun Saiki

Kyoto University, Kyoto, Japan

Author Note

Correspondence regarding this article should be addressed to Jun Saiki, Graduate School of Human and Environmental Studies, Kyoto University, Yoshida, Nihonmatsu-cho, Sakyo-ku, Kyoto 606-8501, Japan.

Tel: +81-75-753-6556

E-mail: saiki@cv.jinkan.kyoto-u.ac.jp

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Abstract

Visually, we can extract a statistical summary of sets of elements efficiently. However, our visual system has a severe limitation in that the ability to recognize an object is remarkably impaired when it is surrounded by other objects. The goal of this study was to investigate whether the crowding effect obstructs the calculation of the mean size of objects. First, we verified that the crowding effect occurs when comparing the sizes of circles (Experiment 1). Next, we manipulated the distances between circles and measured the sensitivity when circles were on or off the limitation of crowding (Experiment 2). Participants were asked to compare the mean sizes of the circles in the left and right visual fields and to judge which was larger. Participants' sensitivity to mean size difference was lower when the circles were located in the nearer distance. Finally, we confirmed that crowding is responsible for the observed results by showing that displays without a crowded object eliminated the effects (Experiment 3). Our results indicate that the statistical information of size does not circumvent the bottleneck of crowding.

(179 words)

Keywords

crowding, statistical summary, mean extraction, size perception

Introduction

Our visual world contains a vast amount of information. Many researchers have shown that the capacity of the human visual system is too limited to grasp all of the visual elements in the visual field (e.g., Treisman & Gelade, 1980). However, information in the real world is often redundant. A particular visual feature in a scene often provides some information on the surrounding features. Thus aggregating properties of individual objects in a scene as a statistical summary is beneficial for efficient representation of the external world. A statistical summary refers to any description that is aggregated from the individual elements, such as the mean, variance and skewness across space and/or time (Alvarez, 2011). There is evidence that we humans are able to register global information from visual elements. With high precision, we can compute the average in the domain of object size (Ariely, 2001; Chong & Treisman, 2003), object orientation (Dakin & Watt, 1997; Parkes, Lund, Angelucci, Solomon, & Morgan, 2001), object motion (Watamaniuk & Duchon, 1992), object location (Alvarez & Oliva, 2008) and facial attributes (Haberman & Whitney, 2007). One possible benefit of computing statistics is to describe our surrounding environment in a compactly-encoded manner and bypass the limited capacity of our cognitive system (Alvarez, 2011).

However, we should take into account the interaction of perceptual limitations with the statistical computation when viewing the periphery. In peripheral vision, the ability to recognize an object is remarkably impaired when it is surrounded by other objects. This phenomenon is commonly known as crowding (Bouma, 1970). Interferences among objects in the peripheral field occur over distances up to about half the eccentricity of the target (Bouma, 1970; Toet & Levi, 1992). Crowding effects have been reported to occur for a wide variety of aspects of an object; e.g., letters (Bouma, 1970; Toet & Levi, 1992), object orientation (Andriessen & Bouma,

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1976; Parkes et al., 2001), and object size (van den Berg, Roerdink, & Cornelissen, 2007).

Although many studies investigated the properties of crowding, it is still unsolved how crowding disturbs the statistical computation. This issue is related to a fundamental question in object recognition: what information passes through or drops out of object processing streams in the limited human vision.

Some studies have focused on the relationship between averaging and crowding (Bulakowski, Post, & Whitney 2011; Parkes et al., 2001). Parkes et al. (2001) demonstrated that judgment of the crowded Gabor orientation was biased toward the average orientation in a display. In the literature, they proposed a pooling model in which orientation signals arising from all of the Gabor patches (including a target and flankers) were compulsorily averaged and observers judged a target orientation based on the pooled information. The model predicted successfully the performance of orientation discrimination. Bulakowski et al. (2011) showed that the perception of the mean line orientation did not vary between the upper and lower visual fields while crowding was stronger in the upper relative to the lower field, suggesting that crowding is dissociated from averaging. However, note that they did not directly investigate whether crowding act as a bottleneck of the process of averaging. In other words, what their results actually indicated was that the mean representation is available under crowding, not that the mean representation was escaped from the deleterious effect of crowding.

Does crowding disrupt the extraction of the mean? This question directly concerns the nature of crowding effect. One hypothesis is that crowding is caused by enforced averaging. Parkes et al. (2001) argued that crowding and texture perception (including averaging process) are opposite sides of the same coin, meaning that crowding effect was essentially the same concept as compulsory averaging of features. According to this idea, crowding effect would not

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at all impair the mean representation. Although their data themselves might not confirm the above hypothesis, consistent results were provided by Fischer and Whitney (2011). For emotion averaging, they showed that unrecognized faces by crowding still contribute to the judgment of the mean facial expression. Their analyses also demonstrated that crowding effect did not predict the averaging performance, suggesting the visual system had access to precise information about the expressions of the crowded faces. An alternative hypothesis is that crowding is more than enforced averaging and obstructs visual representations of individual objects. Dakin, Bex, Cass, and Watt (2009) demonstrated that crowding decreased the precision of the local orientation sample entering the average. They employed a noise analysis and found that the pattern of performance impairment under crowding was explained by the increases in the noise added to each local estimate of oriented patches. Little evidence has been gathered so far to investigate whether or not crowding impairs averaging and previous results are inconsistent. Studies on degradation effect of crowding provide us clues to elucidate whether crowding is simply a compulsory averaging, or it also degrades quality of representation of local elements.

Our goal was to investigate whether crowding acts as a bottleneck for the computation of mean size. A number of studies in the field of average perception within the last decade have shown a growing interest in size information. There are pieces of evidence that our visual system is tightly connected with the statistical representation of size although it remains unclear how it is coded (Alvarez, 2011). For example, Chong and Treisman (2005) suggested that mean size is computed automatically and preattentively. Other research suggested that when remembering multiple objects, their mean size is implicitly encoded and used to reduce uncertainty about the size of individual objects (Brady & Alvarez, 2011). Thus, we evaluated how size averaging is affected by crowding. Note that Chong and Treisman (2005) investigated the effect of the

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density and the numerosity in that domain. They used a set of circles as stimuli and varied the number of circles in the display and the area in which the circles appeared. Then they measured the accuracy of the computation of mean size. They found that the density was not a factor that caused performance improvement or impairment. However, their experiment was not strictly designed to measure the crowding effect. In their experiment, circles were located in an imaginary matrix (where each cell measured $2.6^\circ \times 2.6^\circ$) and two matrices were in the left and right visual fields. The point was that the arrangement of the circles in the matrix was randomly selected from trial to trial. For example, in the condition where circles were crowded by 8 circles, they were randomly distributed in a 3×5 matrix and by 16 circles in a 4×7 matrix. This is quite different from the arrangement of objects for the experiment that aimed to measure the crowding effect, in which target-to-flanker distances were equalized. Previous studies showed that the degree of crowding depended on the distance between the objects (Bouma, 1970; Pelli, Palomares, & Majaj, 2004; Toet & Levi, 1992). Thus, the arrangement of circles can be insufficient to capture the information lost by the crowding effect. In our study, we controlled the center-to-center distance between objects, according to previous studies on crowding.

In Experiment 1, we tested whether the conditions we set actually brought on the crowding effect by the method of constant stimuli and QUEST staircase procedure (King-Smith, Grigsby, Vingrys, Benes, & Supowit, 1994; Watson & Pelli, 1983). Experiment 2 examined the effect of gathering circles on the judgment of mean size. If the crowding involves a deleterious effect on a mean size representation, participants would become less sensitive to the mean size difference because of the inaccurate extraction of the size information of a central circle. In Experiment 3, we tested whether the results in Experiment 2 could be accounted for without the crowding effect by eliminating central circles.

Experiment 1A

We investigated whether the sizes of circles in the periphery were rendered unrecognizable by surrounding circles. Van den Berg et al. (2007) showed that the crowding effect occurred in size judgment, and this experiment therefore corresponded to the replication of their findings using our experimental settings.

If the crowding effect occurs in size judgment, participants would be less sensitive to the difference in size of two circles. Experiment 1A measured the sensitivity to size differences using the method of constant stimuli, which was also used in Experiments 2 and 3.

Methods

Participants

Nine undergraduate students from Kyoto University participated in the study for course credit (5 females, 4 males). All gave informed consent prior to the start of the experiment and had normal or corrected-to-normal vision.

Apparatus

Participants were seated in a dark room. Stimuli were displayed on a 29.8-inch LCD monitor (NEC LCD3090WQi) with a screen resolution of 2560×1600 pixels and a refresh rate of 60 Hz. The viewing distance was 42 cm. The presentation of stimuli was controlled by the Psychophysics Toolbox Version 3 (Brainard, 1997; Pelli, 1997).

Experimental Design

Three independent variables were manipulated in Experiment 1A: the spacing between the center circle (dense vs. sparse), the ratio of the central circle in the left hemifield to that in the right hemifield (seven levels), and the ratio of the average size of the peripheral circles between

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the left and right hemifields (three levels). The three levels of the ratio of peripheral circles were adjusted to the conditions in Experiment 2 (averaging task). We tested whether the crowding occurs in all conditions of peripheral circles used in Experiment 2. The dependent variable was proportion of judgment that the left central circle was larger.

Materials

The stimuli used in our study are shown in Figure 1A. We defined “size” as the area on a power function scale with an exponent of 0.76. This value was based on the literature that investigated the judgment of circle size. Teghtsoonian (1965) found that the judged size of a circle by the method of magnitude estimation followed its area by that function. Chong and Treisman (2003) replicated the result using estimation of the mean size of two circles. Thus, when scaling or averaging circles, we transformed the areas of actual circles using a power function with an exponent of 0.76 and calculated the value. If we needed to present the circles with calculated sizes on the display, we transformed the values back into physical sizes.

[Insert Figure 1 about here]

Each display was divided into two halves vertically, with each containing five circles. Five circles were arranged in a cross-like shape. The background luminance of the monitor was 25.4 cd/m² and the luminance of the circles was 51.0 cd/m².

Circle sizes were determined so as to ascertain the variability in the combination of circle sizes from trial to trial. The repetitive presentation of a specific combination of circle sizes across trials might enable participants to apply judgments not based on the mean computation by learning the pattern of circle sizes. In addition, sizes were also set to have as different values as possible in a display. At the same time, we adjusted independently the size ratio of the central circles and the ratio of the average sizes of the peripheral circles as conditions. See also the

Appendix section for understanding the precise method for generating sizes of the circles in each trial. In the body text, we describe just the proportional relationships between the central circle sizes and the average sizes of peripheral circles.

Spacing. A central circle at each half of the display always appeared at the location where a midpoint of the circle was separated 16° horizontally from a fixation point. The center-to-center spacing between the central circle and four peripheral circles was 3.6° (dense) or 9.6° (sparse). The latter was clearly beyond critical spacing, which is roughly half of the eccentricity (Bouma, 1970; Pelli et al., 2004).

Ratio of the central circle size. The ratio of the central circle size in the left hemifield to that in the right hemifield had seven levels: 0.14, 0.33, 0.6, 1, 1.67, 3, and 7. The values lower than 1 had a reciprocal relationship to the values higher than 1. Their logarithmic descriptions (base 10) were -0.84, -0.47, -0.22, 0, 0.22, 0.47 and 0.84.

Peripheral circle sizes. We defined three conditions regarding the relative average sizes of the peripheral circles: Right-Larger condition, Equal condition, and Left-Larger condition, whose ratios were 0.882, 1, and 1.133, respectively. These settings were actually the same as the way of generating circles in Experiment 2, since the goal of Experiment 1A was to test whether the crowding occurs in the settings used in Experiment 2. Also see the appendix for the mathematical expression for generating central and peripheral circles.

Further size adjustment. All of the circles were scaled by a small multiplicative factor just before presentation. We expected this to discourage participants from using knowledge of previously seen stimuli for judgments (Chong & Treisman, 2003). Three multiplicative factors (1, 1.1 and 1.2) were randomly used in any given trial. This scaling did not affect the size ratio

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manipulations described above. This adjustment was carried out in the final process of generating circles in all experiments.

Procedure

A session was composed of 10 blocks of 84 trials. A practice (84 trials) session preceded the experimental blocks. All participants completed two sessions. Thus, they experienced 1680 judgments ($2 \text{ spacings} \times 3 \text{ ratios of the average size of the peripheral circles} \times 7 \text{ ratios of central circle size} \times 40 \text{ repetitions}$). All conditions appeared within blocks and with equal probabilities.

Each trial began with a fixation cross for 600 ms, followed by circles on both sides of the display for 133 ms. A brief presentation prevented participants from moving their eyes to the circles. They were asked to select the center circle that was larger. They made two-alternative forced choice key-presses (key 1 as “left” and 2 as “right”). A no-response deadline was imposed. They were instructed to respond as accurately as possible.

Data Analysis

At each size ratio of the circles, we obtained the proportion of responses wherein each participant reported the left target to be larger than the right (“left” response). Psychometric curves were fitted with a logistic function, using the `psignifit` toolbox version 2.5.6 from MATLAB (Wichmann & Hill, 2001). To determine the shape of the function, the model considered four parameters: point of subjective equality (PSE), slope, the upper bound and lower bound. At each data point, the size ratio for the central circles was converted into the logarithmic description, the base of which was 10. Logarithmic conversion was to symmetrize the value of the size ratio. The goodness-of-fit of the psychometric curve was assessed using deviance (Wichmann & Hill, 2001). Deviance is a log-likelihood ratio between the data model and a saturated model containing as many parameters as empirical data points, representing how the

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data model deviates from a saturated model. For each data set, a deviance of actual data was calculated from the data model constructed by four parameters (described above). In addition, we carried out bootstrap simulations using the data model and generated new data sets ($N = 10,000$). For each of these simulated data sets, a function was fit and deviance value was calculated. This yielded distributions of deviance and enabled us to evaluate how a deviance of actual data is unlikely. The criterion was whether the deviance value of actual data fell outside the 97.5 percentile of this distribution. The entire data from participants who violated the criterion in any of the data fitting were not included in the analysis.

At each size ratio condition for the central circles, we obtained the proportion of responses in which a left central circle was larger. The slope of the function at the 50% response point was estimated.

Results

The results of the experiment are shown in Figure 2. Of 54 psychometric curves, one empirical deviance was outside the 97.5% of the deviance distributions. Therefore, the entire set of observations from one participant that produced the deviant curves was excluded. The data were analyzed by a 3 (ratio of the average size of peripheral circles: Right-Larger, Equal, or Left-Larger) \times 2 (spacing: 3.6° or 9.6°) analysis of variance. For the repeated measures analyses throughout the entire study in which the assumption of sphericity was violated, we used the Greenhouse-Geisser correction to adjust all degrees of freedom. Generalized eta squared (η_G) was reported in the results as an index of effect size (Olejnik & Algina, 2003). It reflected the proportion of variance that was accounted for by specific factors or their interactions.

[Insert Figure 2 about here]

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The equal differences of slopes between spacing conditions are shown at all relative average sizes of peripheral circles (Figure 2D). An ANOVA revealed a significant main effect of spacing [$F(1, 7) = 44.773$, $MSe = 1.645$, $p < .001$, $\eta_G = .766$]. However, a main effect of the ratio of the average size of peripheral circles was not significant [$F(1.69, 11.86) = .968$, $MSe = .200$, $p = .394$, $\eta_G = .014$]. An interaction effect was also not significant [$F(1.57, 11) = 1.465$, $MSe = .184$, $p = .267$, $\eta_G = .019$].

Experiment 1B

Experiment 1B added more evidence that the sensitivity impairment was really due to crowding. Some other perceptual effects, such as ordinary masking and surround suppression, may reduce the visibility of a target stimulus. Recent work has demonstrated that the crowding is dissociated from other effects by several diagnostic criteria (Pelli et al., 2004). The well-known criterion is critical spacing: the spatial window in which the crowding occurs scales with eccentricity (Bouma, 1970; Toet & Levi, 1992). We adopted this criterion and compared the critical spacings at two eccentricities. Following Pelli et al. (2004) and van den Berg et al. (2007), we used the QUEST method.

Methods

Participants

A total of seven undergraduate and graduate students from Kyoto University participated in the present experiment (2 females, 5 males). All were members of our laboratory. One was an author. All had normal or corrected-to-normal vision.

Experimental Design

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Three independent variables were manipulated: eccentricities (10° , 16°), spacing (nine levels) and ratio of the central circle (modulated by the QUEST). The ratio of the peripheral average circle sizes was fixed to be 1. Size difference between central circles was compared by participants. Unlike Experiment 1A, thresholds of size discrimination were measured.

Materials

The materials were identical to Experiment 1A except for the following changes. The luminance of the background and the circles was 25.3 cd/m^2 and 50.8 cd/m^2 , respectively.

Spacing. Different sets of spacing were prepared at different eccentricities (10° , 16°) to measure around the critical spacing. At 10° of eccentricity, the set of spacings were 3.6° , 3.88° , 4.16° , 4.44° , 4.72° , 5° , 5.5° , 6° , and 7° . At 16° of eccentricity, 3.6° , 4.48° , 5.36° , 6.24° , 7.12° , 8° , 8.8° , 9.6° , and 11.2° .

Ratio of the central circle size. The ratio of the central circle size was determined by the QUEST staircase procedure, which assumes a Weibull psychometric function and determines a size ratio to make a certain level of correct performance. In the current experiment, the level was 82%. The slope parameter β was set as 3.5°^{-1} , and the guess rate γ was set as 0.5.

Procedure

Participants judged which central circle was larger (Figure 1A). A practice (90 trials) preceded the experimental run. Thresholds were estimated based on measurements of 50 trials. Each threshold was measured twice per participant and averaged. Participants experienced 1800 judgments ($2 \text{ eccentricities} \times 9 \text{ spacings} \times 50 \text{ trials} \times 2 \text{ runs}$). All conditions appeared within blocks.

Data analysis

When thresholds were plotted against spacing, they generally had a sigmoidal shape. The critical spacing was the spacing at which a threshold elevation occurred. Pelli et al. (2004) fitted a simple model to the data to determine the critical spacing. The model consisted of a threshold ceiling, a threshold floor, and a linear transition between the two. A least squares method was used for the model fitting. Critical spacing was computed as the intersection between the transition and the floor.

Results

Figure 3 represents thresholds of size discrimination as a function of spacing between the target and flankers. One participant showed extremely low thresholds across the spacings at an eccentricity of 10° so that the model could not be fitted. We excluded this entire dataset from the analysis. The critical spacings were compared by a one-factor analysis of variance.

[Insert Figure 3 about here]

The group results showed that the critical spacing at 10° of eccentricity was smaller than that at 16° of eccentricity (Figure 3A). The main effect of eccentricity was significant [$F(1, 5) = 14.571$, $MSe = .733$, $p = .007$, $\eta_G = .759$]. In addition, the estimates were about $0.4 \times$ eccentricity, which was consistent with the key signature of crowding. Figure 3B represents the individual estimates of the critical spacings. For all participants, estimates at 16° of eccentricity were below 9.6° , at which we considered no crowding occurred in Experiment 1A. Note that we avoided evaluating threshold ceiling due to the constraint of the experimental setting of spacing condition. Smaller spacings less than 3.6° result in the spatial overlap between a target and flankers. A threshold elevation by spatial overlap represents ordinary masking, not crowding effect (Pelli et al., 2004).

Discussion

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The results suggested that participants showed greater difficulty in having access to the size information of the central circles as peripheral circles approached the center circles, which is consistent with van den Berg et al. (2007). We verified that spacing parameters (3.6° or 9.6°) were allowed for testing whether or not the crowding effect served as a bottleneck at the calculation of the mean circle size.

Experiment 2

Experiment 2 was conducted to measure the ability to compare the sizes of circle sets. We hypothesized that the crowding would impede accurate extraction of the size information of a center circle, which would result in insensitivity to the mean size difference.

Methods

Participants

A total of 21 undergraduate and graduate students from Kyoto University participated in the present experiment (9 females, 12 males). Ten were members of our laboratory including one author and eight naive participants that received 1000 yen/hr. All gave informed consent prior to the start of the experiment and had normal or corrected-to-normal vision.

Experimental Design

As with Experiment 1A, three independent variables were manipulated: the spacing (dense vs. sparse), the ratio of the central circle (five levels) and the ratio of the peripheral average circle sizes (three levels). The average size of five circles (five levels) was estimated by participants. The dependent variable was the proportion of judgments that the average size of the five circles in the left hemifield was larger than the average size in the right hemifield.

Materials

The materials were the same as those in Experiment 1A and 1B, except for the following changes (also see the Appendix). The background luminance and luminance of the circles were slightly different from the luminances in Experiment 1A and 1B (26.0 cd/m^2 and 51.1 cd/m^2 , respectively). An example of the stimuli is shown in Figure 1A.

Ratio of average circle sizes. The ratio of the overall average sizes of five circles in the left hemifield to that in the right hemifield had five levels regardless of the condition of the ratio of the average size of the peripheral circles; 0.81, 0.90, 1, 1.11 and 1.22. Their logarithmic descriptions (base 10) were -0.09, -0.04, 0, 0.04 and 0.09. As in Experiment 1A, the ratio of the average size of the peripheral circles had three levels (Right-Larger, Equal and Left-Larger). The marked difference was that a different set of ratios for the central circle sizes for each level was used. This was because the set of the ratio of the overall average circle sizes was made constant across different conditions of the average sizes of the peripheral circles. The actual relationship between central and peripheral circle sizes in each condition is written in the following sections.

Central circle size. The ratio of the central circle size in the left hemifield to that in the right hemifield had five levels. However, actual values were different between the three conditions of the peripheral sizes. The values were 0.6, 1, 1.67, 3, and 7 in the Right-Larger condition; 0.33, 0.6, 1, 1.67, and 3 in the Equal condition; and 0.14, 0.33, 0.6, 1, and 1.67 in Left-Larger condition.

Procedure

The sequence of this experiment was the same as in Experiment 1A. In Experiment 2, however, participants were asked to select a circle array whose average size was larger.

A session was composed of 10 blocks of 75 trials. A practice (90 trials) session preceded the experimental blocks. All participants completed two sessions. Thus, they experienced 1500

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judgments (2 spacings \times 3 ratios of the average size of the peripheral circles \times 5 ratios of central circle size \times 50 repetitions). All conditions appeared within blocks and with equal probabilities.

Data Analysis

Psychometric functions were estimated in the same manner as in Experiment 1A. The sensitivity to the mean size difference was tested using the slope of the functions.

Results

Figure 4 shows the performance when comparing the mean sizes of the circles. The total percentage correct from one participant was poor (below 60%). In addition, of the remaining 120 psychometric curves, three empirical deviances were outside the 97.5% of the deviance distributions. Therefore, the entire dataset from four participants were excluded. The data were analyzed by a 3 (ratio of the average size of the peripheral circles) \times 2 (spacing) analysis of variance.

[Insert Figure 4 about here]

The fact that psychometric curves were shallower at dense spacing indicated that participants were less sensitive to the differences of the mean sizes when the circles were more crowded (Figure 4D). The main effect of the spacing was significant [$F(1, 16) = 11.537$, $MSe = 4.579$, $p = .004$, $\eta_G = .132$]. However, the main effect of the ratio of the average size of the peripheral circles was not significant [$F(1.97, 31.57) = .065$, $MSe = 1.061$, $p = .935$, $\eta_G = .0004$]. Spacing \times the ratio of the average size of the peripheral circles interaction was also not significant [$F(1.97, 31.53) = 1.669$, $MSe = .723$, $p = .205$, $\eta_G = .007$]. They indicated that the loss of sensitivity due to the increased crowding effect was equal regardless of the ratio of the mean sizes of the surrounding circles between the two halves of the display.

Discussion

The more crowded the circles, the poorer the participants' sensitivity to the mean size of the circles. This suggested that the size crowding effect deteriorated the mean estimation. Of course, the effect of crowding was unlikely to be limited to the center circle since the peripheral circles came close to other circles in the neighborhood. However, the surrounding circles were not blocked in four directions as with the central one, so it is natural to think that the effect of crowding had the biggest influence on the central circle in Experiment 2.

Experiment 3

In Experiment 3, we tested whether the results in Experiment 2 actually reflected the crowding effect. An alternative account for the results of Experiment 2 is that the difference in the arrangement of peripheral circles improved sensitivity in the sparse condition. Namely, circles in the display had different distances from the fovea (fixation point) between the dense and sparse conditions. In particular, a circle closest to the fixation point had smaller eccentricity in the sparse condition than in the dense condition. Given that perceptual acuity improves with decreasing eccentricity (Anstis, 1998), if participants relied more on the circle nearest to the fixation in their judgment, the advantage in the sparse condition may be due to the smaller eccentricity of the nearest circle compared with the dense condition. Experiment 3 eliminated the central circles from the display used in Experiment 2. If the arrangement of the peripheral circle was responsible for the results of Experiment 2, the same result should be obtained. In contrast, if the crowding effect was responsible, the effects observed in Experiment 2 should disappear.

Methods

Participants

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Eighteen undergraduate students from Kyoto University participated in the experiment for course credit (7 females, 11 males). All gave informed consent prior to the start of the experiment and had normal or corrected-to-normal vision.

Experimental Design

Two independent variables were manipulated: the spacing (dense vs. sparse) and the ratio of the average size of the peripheral circles (seven levels). The dependent variable was the proportion of judgments that the average size of the four circles in the left hemifield was larger than the average size in the right hemifield.

Materials

The materials were the same as those in Experiments 1 and 2, except for the following changes (also see the Appendix). An example of the stimuli is shown in Figure 1B. Each half of the display had circles with a central circle eliminated. Four remaining circles were kept and arranged in a cross-like shape. The background luminance of the monitor was 25.4 cd/m^2 and the luminance of the circles was 51.1 cd/m^2 .

Ratio of the average circle size. The ratio of the average sizes of the four circles in the left hemifield to that in the right hemifield had seven levels with values slightly different from Experiment 2; i.e., 0.83, 0.88, 0.94, 1, 1.06, 1.13 and 1.21, respectively. Their logarithmic descriptions (base 10) were -0.08, -0.05, -0.03, 0, 0.03, 0.05 and 0.08, respectively.

Procedure

The sequence of this experiment was the same as in Experiment 2. A session was composed of 10 blocks of 70 trials. A practice (70 trials) session preceded the experimental blocks. Participants experienced 700 judgments ($2 \text{ spacings} \times 7 \text{ ratios of the average size} \times 50 \text{ repetitions}$). All conditions appeared within blocks.

Results

The performance when comparing the mean sizes of the circles is shown in Figure 5. All deviances from 36 psychometric curves were within the 97.5% of the deviance distributions and all data were included in the analysis. The data were analyzed by a one-way analysis of variance (spacing: 3.6° or 9.6°).

[Insert Figure 5 about here]

The slopes between the two spacing conditions were not different (Figure 5B). The main effects of the ANOVA did not reach significance [$F(1, 17) = .177$, $MSe = .610$, $p = .680$, $\eta_G = .003$]. In the same manner, The PSE values (50% thresholds) revealed no differences [$F(1, 17) = 2.50$, $MSe = .001$, $p = .133$, $\eta_G = .006$].

Discussion

Taken together, the results suggested that the precision, when calculating the mean size of the peripheral four circles, was not affected by the arrangement of the circles. In our experiment, it is unlikely that any effect other than the interference between the central and peripheral circles explained the results for Experiment 2.

General Discussion

The current study tested how crowding affects the mean size judgment of circles. Our results suggested that the interference between dense circles impairs the sensitivity to size information.

We provided new evidence about the relationship between averaging and crowding. The current study is the first to report the average information of sizes does not circumvent the bottleneck of crowding. It is consistent with the study by Dakin et al. (2009)'s study,

demonstrating the deleterious effect of crowding on averaging. Meanwhile, the study contradicts with the claim by Fischer and Whitney (2011). Their results indicated that the visual system fully maintains the average representation of facial expressions (disgust) even when a set of faces were crowded. Because we also verified that the interference between target and flankers is responsible for performance impairment (Experiment 1 and 3), it is unlikely that we actually measured any confounding factor other than crowding effect.

Our results suggest that, in the domain of size, the visual process involved in averaging is not equated with crowding. Parkes et al. (2001) found that when judging the orientation of a crowded Gabor patch, observers showed biased responses toward the average orientation in a display. Based on the results, they argued that crowding and texture perception (e.g., averaging) are opposite sides of the same coin, meaning that crowding effect was just the other view of compulsory averaging. According to this idea, crowding would not at all impair the mean representation. This claim accords with a prominent explanation of crowding: crowding is a product of faulty information pooling (Levi, 2008; Pelli et al., 2004; Pelli & Tillman, 2008). Pelli et al. (2004) referred to the “integration field”, which is the spatial extent over which features of objects are mandatorily combined, and explained the crowding effect using this field. A similar idea was proposed using the concept of the minimum of attentional resolution (Intrilligator & Cavanagh, 2001). When the target and flankers are within the same field, their features are pooled together, which hampers conscious access to the individual objects. However, what Parkes et al. actually showed was that a mean representation of features was available under crowding, not that the information was transformed into the mean with no cost. Based on our data, we argue that the visual process involved in crowding includes interferential process which disrupts the size representation.

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An important question is why crowding effects influenced on averaging of size and orientation, but not on averaging of facial expressions. First, crowding effect of face may occur at multiple levels in the visual system while averaging may not. The widely-held notion is that holistic processing plays a crucial role in recognizing facial properties (Maurer, Le Grand, & Mondloch, 2002). The term *holistic* generally refers to integrating featural and spacing information in a unified representation (Wilford & Wells, 2010). Recent studies demonstrating crowding effect of facial stimuli suggested that crowding effect occurs between the holistic representation of faces (Farzin, Rivera, & Whitney, 2009) and between component-based representations such as eyes, brow and mouth (Martelli, Majaj, & Pelli, 2005). When the crowding effect of faces is observed, it could be a compound effect of crowding at different levels. However, Fischer and Whitney (2011) reported that when crowded faces were inverted or scrambled (local patches of face images were swapped), in which holistic information was disrupted, their influence on the judgment of facial expressions was eliminated, suggesting that the mean computation of emotions of crowded faces is purely a holistic-based perception. The crowding effect in holistic processing might be insufficient to show a robust influence on the mean representation. Because holistic processing is unique to faces or face-like objects (Maurer et al., 2002), features other than face may not show benefit of holistic representations in mean perception, leading to impairment in averaging performance by crowding effect. Second, a pathway specific to emotional information may not have a deleterious effect when averaging the information. It has been suggested that face processing occurs along a subcortical extrageniculostriate pathway comprising the superior colliculus, the pulvinar, and the amygdala, which bypasses the temporal visual pathway (Morris, DeGelder, Weiskrantz, & Dolan, 2001; Vuilleumier, Armony, Driver, & Dolan, 2003). There is some evidence that the neural

representation of faces differs across different pathways (Inagaki & Fujita, 2011; Vuilleumier et al., 2003), which might lead to the difference in the costs between the mean computation of circle sizes and emotions. Third, the diagnostic information for emotion perception may simply be more redundant than the information for size perception, thus emotion perception may be less susceptible to the degradation of local element representations than size perception. Logically, circle size is merely specified by the maximum distance between contours comprising a circle shape, in contrast with facial expression which might rely on multiple types of cues (holistic and component-based). This difference in quality of local elements may affect the accuracy of mean perception, but not crowding, because compulsory averaging leads to crowding regardless of their quality.

The current experiments were similar to those employed in the study by Choo and Franconeri (2010) in that both studies explored whether object information with reduced visibility contributed to size averaging. However, their results were opposite to ours. They manipulated the visibility of circles using object substitution masking (OSM). In their experiments, some circles in the display were surrounded by four-dot masks that lingered longer than the circle array. The experiments demonstrated that masked circles still contributed to the perceived average size as much as circles without the OSM even if identification was significantly impaired by the OSM. This may be explained by the difference in processing stages involved in OSM and the crowding. The dominant view of OSM is that it emerges late in the course of visual processing. The mask substitutes for an initial representation of the object within an iterative sequence of feed-back from higher visual areas (Di Lollo, Enns, & Rensink, 2000, 2002; Enns, 2004, Enns & Di Lollo, 1997). As suggested by Choo and Franconeri, the average is calculated from early object representations before OSM. Meanwhile, another study found that

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the level at which crowding takes place was earlier than OSM in the processing stage (Chakravarthi & Cavanagh, 2009). Chakravarthi and Cavanagh masked only the flankers (but not the target) with OSM in their crowding experiments. If OSM disrupted the processing of flankers, the target visibility would be recovered. However, they showed that OSM did not produce any target recovery. This suggested that the interaction between the flankers and the target occurred before OSM became effective. Our results expand the understanding of the visual processing stream. The extraction process of mean size information might intervene between the stages where OSM and crowding take place in the visual processing stream.

Recently, Palomares and Pitts (2011) reported the opposite results regarding the relationship between size averaging and crowding. They concluded that the accuracy of explicit averaging (asking about the average size for the task) was unaffected by the spacing between the target and flankers. One speculation is that the strength of the crowding by flankers between our experiments and theirs was different. They used only two flankers. Pöder and Wagemans (2007) found a substantial set-size effect in crowding. The strength of crowding correlated with the number of flankers. In addition, their flankers had tangential locations. The crowding had radial/tangential anisotropy (Toet & Levi, 1992). The flankers in the tangential direction had a much weaker effect of crowding than the flankers in the radial direction. The crowding effect might be insufficient to observe the impairment of the mean computation in their experiments.

Finally, we note a possibility that crowding has a direct influence on the statistical representation, not on individual objects. Our results cannot give an unambiguous answer because we did not analyze how the performance impairment by crowding correlates with the impairment of averaging. If crowding just affects local estimates, the accuracy of mean size judgments would be perfectly predicted from the accuracy of size judgments of individual

objects. Nevertheless, there is evidence negating this possibility. Dakin et al. (2009) proposed a model and showed that crowding affected the local noise of each orientation estimate, not the *efficiency* (the effective number of elements they can average over) with which these estimates can be globally pooled. Although there are various interpretations of the efficiency, a reduction in efficiency might be equivalent to a reduction in the gain on the response of neurons pooling estimates (Dakin, Mareschal, & Bex, 2005).

In conclusion, the data reported here demonstrated that the computation of mean circle size does not fully circumvent the crowding effect. We found that interference among dense circles impaired sensitivity to the mean size judgment suggesting that the visual process involved in crowding is not equated with the averaging computation of size.

Acknowledgments

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Figure Captions

Figure 1.

Trial schematics for Experiments 1-3. (A) A schematic illustration for Experiments 1A, 1B, and 2. Participants compared the sizes of the central circles (Experiment 1A, 1B) or the mean sizes of 5 circles (Experiment 2). (B) A schematic illustration for Experiment 3 in which participants compared the mean sizes. Note that the sizes of circles and fixations in relation to the monitor frame are different from the sizes in an actual display for the purpose of visualization.

Figure 2.

Data of Experiment 1A. Sensitivity to size differences was quantified as the steepness of the slope in the psychometric curve. (A-C) Proportion “left” responses and fitted psychometric curves at each ratio of the average size of the peripheral circles: Right-Larger (A), Equal (B), and Left-Larger condition (C). The data points are the means from individual data. The curves were calculated from the mean parameter values. Size ratios in the x -axis are written as a logarithmic scale. (D) Slope values at each relative average size of the peripheral circles. Error bars indicate standard errors of the mean. The values were obtained where the proportion of “left” responses reached 0.5.

Figure 3.

Data of Experiment 1B. Identification threshold as a function of spacing between the target and flankers. (A) Thresholds and fitted functions at each eccentricity. The data points are the means

from individual data. The curves were calculated from the mean parameter values. The function was drawn from the mean of the individual parameters that decided a threshold ceiling, a threshold floor, and the linear transition between the two. (B) Critical spacings at each eccentricity. Each point represents one participant.

Figure 4.

Data of Experiment 2. (A-C) Proportion “left” responses and fitted psychometric curves at each ratio of the average size of the peripheral circles: Right-Larger (A), Equal (B), and Left-Larger condition (C). The data points indicate the means from individual data. The curves were calculated from the mean parameter values. Size ratios in the x -axis are written as a logarithmic scale. (D) Slope values for each relative average size of the peripheral circles. Error bars indicate one standard error of the mean. The values were obtained where the proportion of “left” responses reached 0.5.

Figure 5.

Data of Experiment 3. (A) Proportion of “left” responses and fitted psychometric curves. The data points indicate the means from individual data. The curves were calculated from the mean parameter values. Size ratios in the x -axis are written as a logarithmic scale. (B) Slope values with standard errors of the mean. The values were obtained where the proportion of “left” responses reached 0.5.

Appendix

The way of generating circle sizes: mathematical presentation

In all experiments, one seed circle size value, called S , was randomly chosen from seven candidates (the remaining six values were also used later to generate the sizes of the peripheral circles). S was not the diameter, but the area on a power function scale with an exponent of 0.76. When the seed values were transformed into the description of diameters, they ranged from 1.2° to 2.46° . All central and peripheral circle sizes evolved around the value S . Sizes for the left and right central circles were obtained by scaling S with the factor of $(1+x)$ and $(1-x)$ using variable x . This corresponds to expanding the seed circle at one hemifield and contracting at the other hemifield. The size ratio of the central circle size was the following ratio:

$$\frac{(1+x)S}{(1-x)S} = \frac{(1+x)}{(1-x)} \quad (1)$$

This ratio was the criterion for judgment in Experiments 1A and 1B.

Peripheral circles were made as follows. First, four seed values were randomly selected from the remaining six values at each hemifield without replacement. This confirmed that the display had as wide a range of circle sizes as possible. The sum of sizes of peripheral circles can be calculated at each hemifield. Next, sizes for the sum of the left and the right peripheral circles were scaled so that the resulting sums were equal to $(4+y)S$ and $(4-y)S$ using variable y . Four circles at each hemifield were equally expanded or contradicted. The mean size of all (eight) peripheral circles was S , which was equal to the seed value for the central circles. The ratio of the mean size of the peripheral circles, which was related to judgments in Experiment 3, is represented in the following way:

$$\frac{(4+y)S}{(4-y)S} = \frac{4+y}{4-y} \quad (2)$$

Finally, the ratio of the average size of all the circles corresponded to the ratio of the sums of the central and peripheral circle sizes in the left and right hemifields. Using x and y , it is represented as:

$$\frac{(1+x)S + (4+y)S}{(1-x)S + (4-y)S} = \frac{5 + (x+y)}{5 - (x+y)} \quad (3)$$

This ratio was the criterion for judgment in Experiment 2.

After deciding central and peripheral circle sizes, all of the circles were scaled by a small multiplicative factor to discourage participants from using knowledge of previously seen stimuli for judgments. Three multiplicative factors (1, 1.1 and 1.2) were randomly used in any given trial. This scaling did not change the ratio because the factor in the numerator and denominator were cancelled.

The parameters.

In Experiment 1A, the y values were -0.25, 0, and 0.25. By Equation 2, the ratios of the average size of peripheral circles were given: 0.882 (Right-Larger), 1 (Equal), and 1.133 (Left-Larger). The x values were 0.75, -0.5, -0.25, 0, 0.25, 0.5 and 0.75 across these conditions. Equation 1 gave the ratios of the central circle size in the left hemifield to that in the right hemifield; 0.14, 0.33, 0.6, 1, 1.67, 3, and 7, respectively. Their logarithmic descriptions (base 10) were -0.84, -0.47, -0.22, 0, 0.22, 0.47 and 0.84.

In Experiment 1B, the y was fixed to 0, because the task was time-consuming. The x value in each trial was changed based on the QUEST method.

In Experiment 2, the y and the ratio of the average size of peripheral circles were the same as in Experiment 1A. The x values were associated with the y with the sum of x and y equated ($-0.5, -0.25, 0, 0.25$, and 0.5) across the ratios of the peripheral average circle sizes: $-0.25, 0, 0.25, 0.5$ and 0.75 (Right-Larger); $-0.5, -0.25, 0, 0.25$ and 0.5 (Equal); and $-0.75, -0.50, -0.25, 0$ and 0.25 (Left-Larger). By Equation 3, the overall ratio of the average circle sizes were found to be the same; $0.81, 0.90, 1, 1.11$ and 1.22 . Their logarithmic descriptions (base 10) were $-0.09, -0.04, 0, 0.04$ and 0.09 .

In Experiment 3, the y values were $-0.375, -0.25, -0.125, 0, 0.125, 0.25$, and 0.375 . No x values were defined because the central circles were eliminated from the display. Therefore, the ratios of overall average circle sizes were decided by Equation 2; i.e., $0.83, 0.88, 0.94, 1, 1.06, 1.13$ and 1.21 . Their logarithmic descriptions (base 10) were $-0.08, -0.05, -0.03, 0, 0.03, 0.05$ and 0.08 .

All ratios lower than 1 had a reciprocal relationship to the values higher than 1. Their logarithmic descriptions were symmetric across 0.

The Ebbinghaus illusion effect.

One might argue that reducing the distance between circles triggers not only crowding, but also a contrast effect of size. This is widely known as the Ebbinghaus illusion. Considering this possibility is important because mean size computation of participants is based on the perceived size modulated by the illusion rather than physical size (Im & Chong, 2009). In the best known version of this illusion, the sizes of peripheral circles (inducers) are identical. In contrast, we chose different sizes of circles in each hemifield. To the best of our knowledge, the strength of the illusion with heterogeneous circle sizes has not been tested. Suppose that the strength of the

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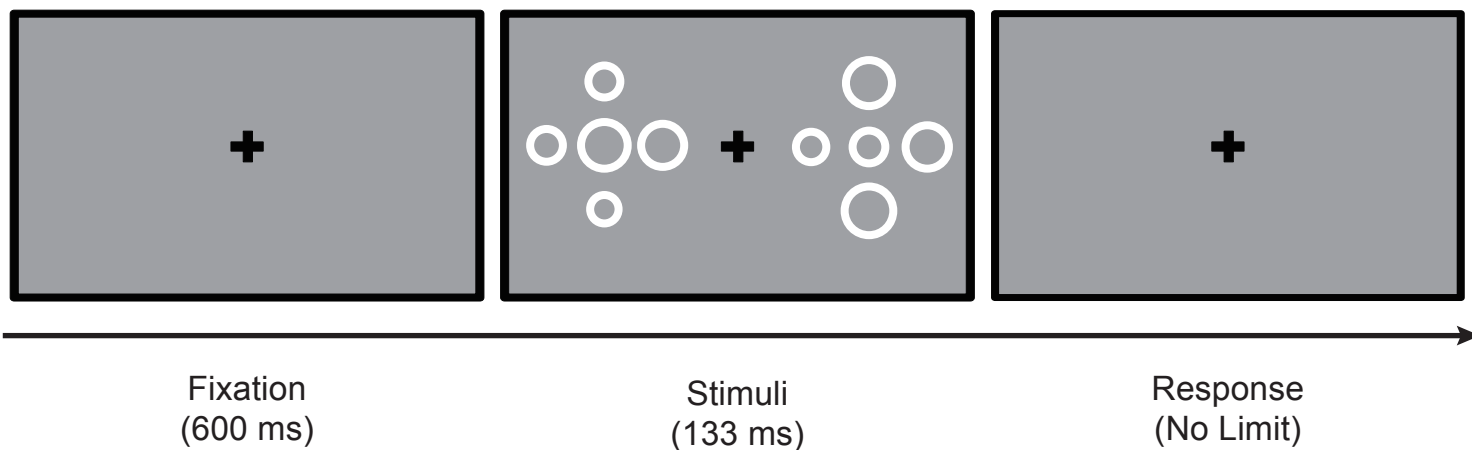
illusion with heterogeneous circles was determined by the size contrast of the central circle and the average size of peripheral circles. The data in Experiment 1A enabled us to examine the shift of points of subjective equality (PSE) brought by peripheral circles. As noted, Experiment 1A had three conditions of peripheral circles: Right-Larger, Equal and Left-Larger. If the Ebbinghaus illusion had an effect, the responses should be biased toward increasing “left” responses in the Right-Larger condition compared with other conditions. Likewise, the “right” response bias should increase in the Left-Larger condition. However, the analysis of the PSE values (50% thresholds) did not show this pattern. Although the PSE values were different at 3.6° spacing [$F(1.58, 9.49) = 14.685$, $MSe = .007$, $p = .002$, $\eta_G = .211$], multiple comparisons revealed that the PSE for the Right-Larger condition was significantly larger than the others ($ts > 3.99$, $ps < .01$). The PSE change indicated that the psychometric curve in the Right-Larger condition was placed more rightward than other conditions in the graph (Figure 2A). This implied a bias toward fewer “left” responses in the Right-Larger condition, opposite to the Ebbinghaus illusion. No significant differences were observed at 9.6° spacing [$F(1.97, 11.8) = 2.598$, $MSe = .0008$, $p = .117$, $\eta_G = .064$]. The result did not validate the Ebbinghaus illusion effect.

Reference

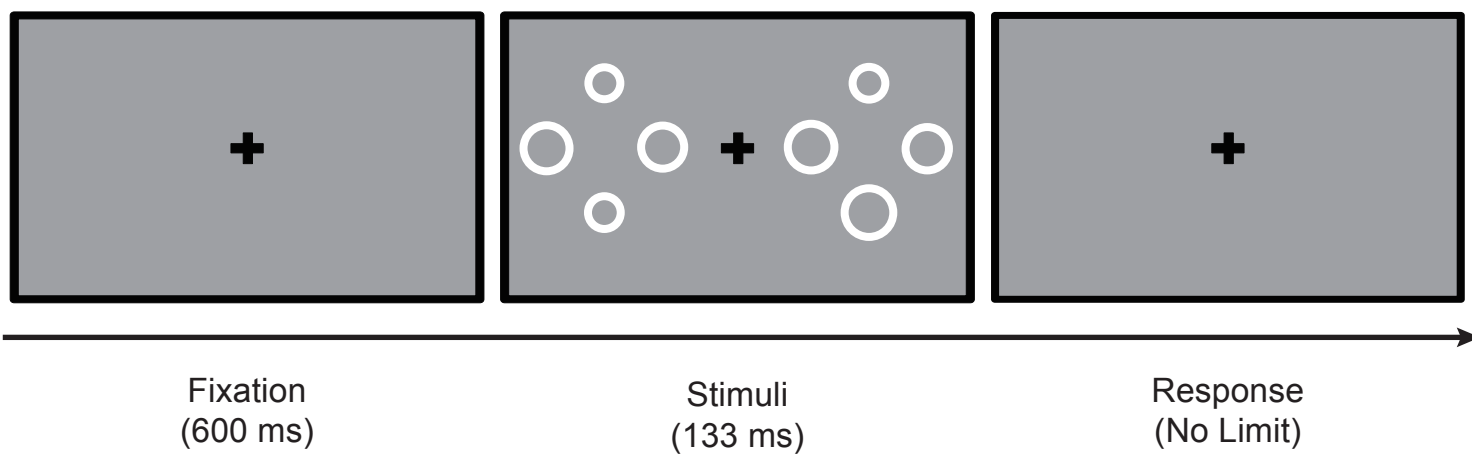
Im, H. Y., & Chong, S. C. (2009). Computation of mean size is based on perceived size.

Attention, Perception, & Psychophysics, 71, 375-384. doi:10.3758/APP.71.2.375

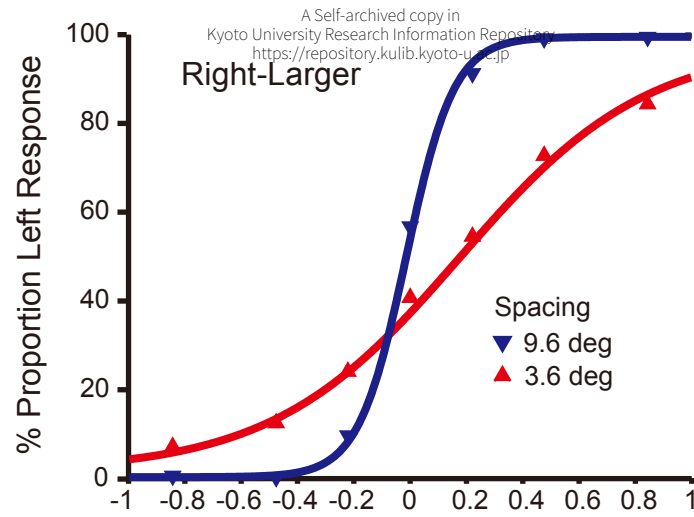
A



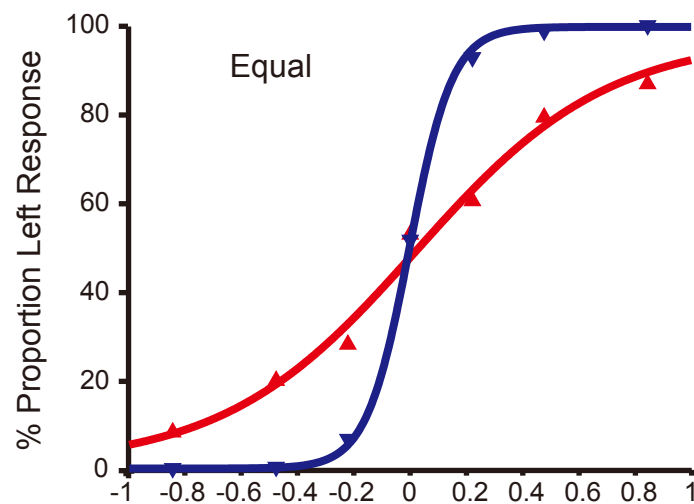
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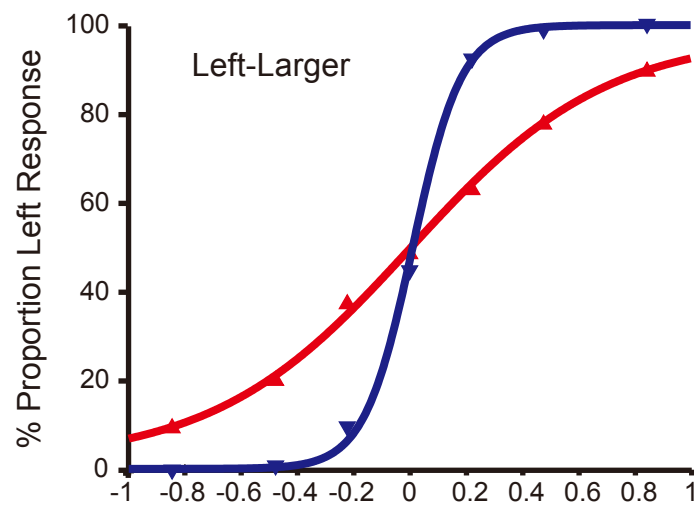
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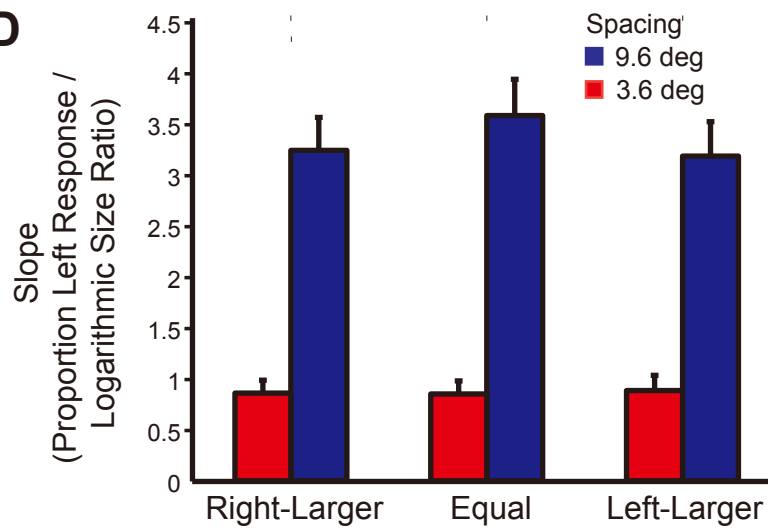


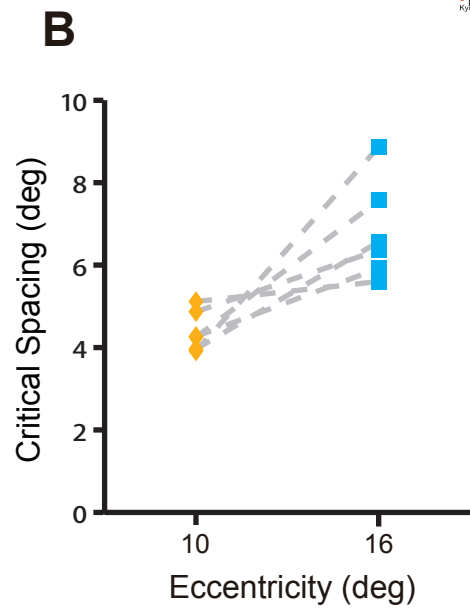
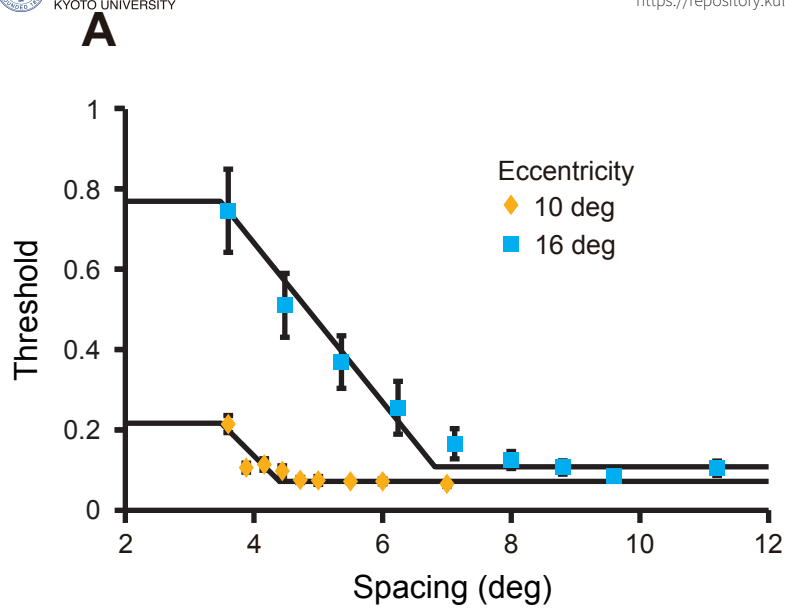
C



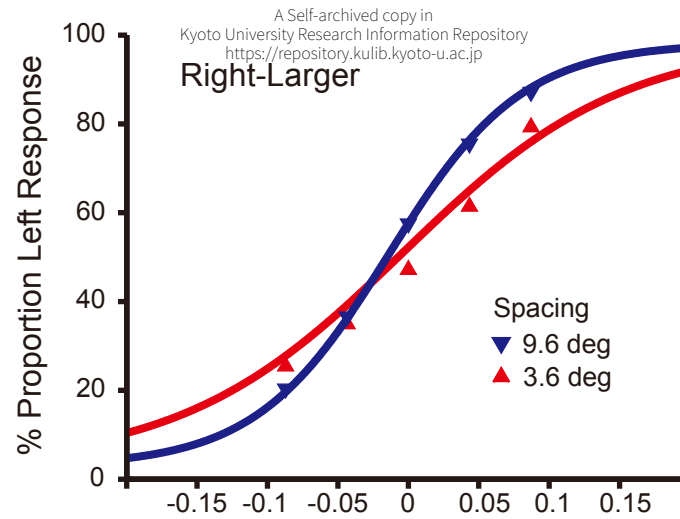
Logarithmic Size Ratio
(Left Center Circle / Right Center Circle)

D

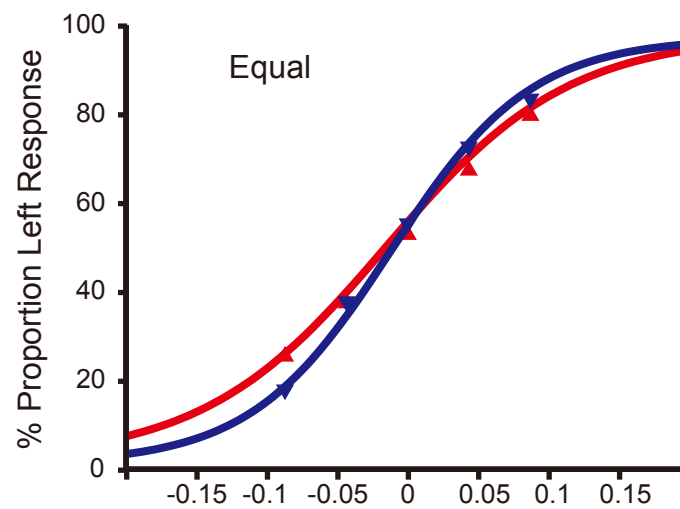




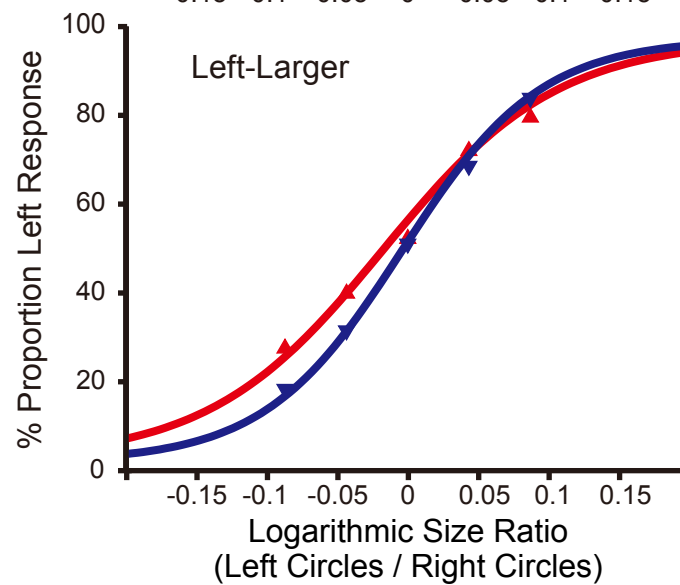
A



B



C



D

